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by M. N. Stoyanova

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THE NATURE OF A WEAK CHROMOSPHERIC FLARE

M. N. Stoyanova

ABSTRACT

The author's studies were made on a very weak flare observed on 3 September 1962 at Pulkovo, using a horizontal solar telescope. Spectrograms were obtained for the H_α and He D_3 segments. Fluctuations in the image did not exceed 2'' in amplitude on that day. The contours of the D_3 line are very shallow, suggesting the possibility that the optical thickness of the flare was slight. The author computed numbers of atoms along the line of sight (1 cm^2 cross section) for the second and third levels and found the ratio to be $1.27 \cdot 10^{-2}$ (upper level to lower level), which compares favorably with the theoretical value of $1.3 \cdot 10^{-2}$. The contours for emission and absorption of the D_3 line are shown in Figure 1 on the Enclosure. These exhibit a Gaussian form. The contours for H_α, shown in Figure 2 on the Enclosure, are not Gaussian, however. In seeking an explanation for these latter contours, the author found that for any assumed relative optical thickness in the flare, a source function was obtained that was larger throughout the contour than the function obtained from population tables corresponding to the case of photospheric radiation. The author concludes that the observed radiation was not caused by scattering, and for this reason the assumption that the source function changes along the contour does not hold (since the self-radiation does not depend on radiation flux). On the assumption of a constant value of the source function, the author examined one-layer models with first a thin, then a thick optical thickness. Neither explained the shape of the contour, and the author then investigated a two-layer model. This furnished an explanation, and it was concluded that the emission of hydrogen cannot be explained by scattering of photospheric radiation, but is caused by an increased population at the third level.

There are many very weak chromospheric flares which are not recorded because of their weakness and the transient nature of the Solar Reporting Service. In some cases these flares remind us of the "whiskers" investigated by A. B. Severnyy, but with considerably smaller contour wings. In the foreign literature these flares are often termed subflares or preflares. A number of articles in the Bulletin of the Astronomical Observatory (Ondrzejov), Czechoslovak Academy of Sciences (Ref. 1) investigate such flares.

The flare we observed on September 3, 1962, at Pulkovo, with the horizontal solar telescope is one of these very weak formations. This flare was located on the east limb of the solar disk, several seconds of arc from its edge. At the same time, we observed luminescence at the same place above the edge of the disk, but it was more of the nature of an extension of the flare.

Photographs were taken in the first order of the grating with Kodak-oaF and Agfa Spektral red fast plates. At the same time, we obtained spectrograms of the H_α and the He D_3 regions. Because of the weakness and transient nature of the emission, we were not able to obtain a larger number of photographs. Fluctuations in the image did not exceed 2" in amplitude on that day.

The plates were developed under standard conditions and photometric readings were taken with a recording microphotometer. Two spectrograms of the flare, separated by a time interval of approximately 1 to 2 minutes, did not reveal any great differences when processed. Contours were constructed for the H_α and D_3 lines of both disturbed regions. All contours (with the exception of the absorption D_3 line) were constructed in units of the continuous spectrum of the center of the sun's disk. The contours of the lines of the formation behind the sun's disk were free of the influence of scattered light from the sky.

1. Processing the He D_3 Lines

The D_3 line on the disk at the site of the flare was visible for absorption. The contour of the line was very shallow, which made it natural to assume small optical depth of the formation.

By making use of the equivalent width of an absorption line, we can determine the total number of atoms along the line of sight (in a 1 cm^2 section) on the lower 2^3P level from the formula

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$$W_\lambda = \frac{\pi e^2 \lambda^2 f_n N_{2P}}{m_e c^2} \qquad (1)$$

The number of atoms on the upper level, N_{3D}, is determined from the D_3 emission contour by the observed intensity:

$$\frac{4 \pi Iv}{Ahv} = N_{3D}. \qquad (2)$$

The following values of the number of atoms were obtained from these formulas:

$$N_{2P} = 2.95 \cdot 10^{11}$$

$$N_{3D} = 3.75 \cdot 10^{9}.$$

The theoretical value of the ratio of populations of the 3^3D and 2^3P levels, taken from tables included in an article by V. A. Krat and V. M. Sobolev (Ref. 2), was constant over a fairly wide range of values of the electron temperature T_e and the electron concentration n_e, and was equal to $1.3 \cdot 10^{-2}$. The ratio of the number of atoms obtained from our observations is $N_{3D}/N_{2P} = 1.27 \cdot 10^{-2}$, i.e., the ratio of the numbers of atoms yielded by these equations (obtained from different formations), coincides with the theoretical value of the ratio of populations. Thus, it is natural to assume that the geometric thicknesses of both formations are approximately the same, and it is possible that the physical conditions in them are identical. The validity of this assumption is also confirmed in the external appearance of both contours (see Figure 1); they do not indicate any noticeable radial velocity, are of Gaussian form, and their half-widths are approximately identical.

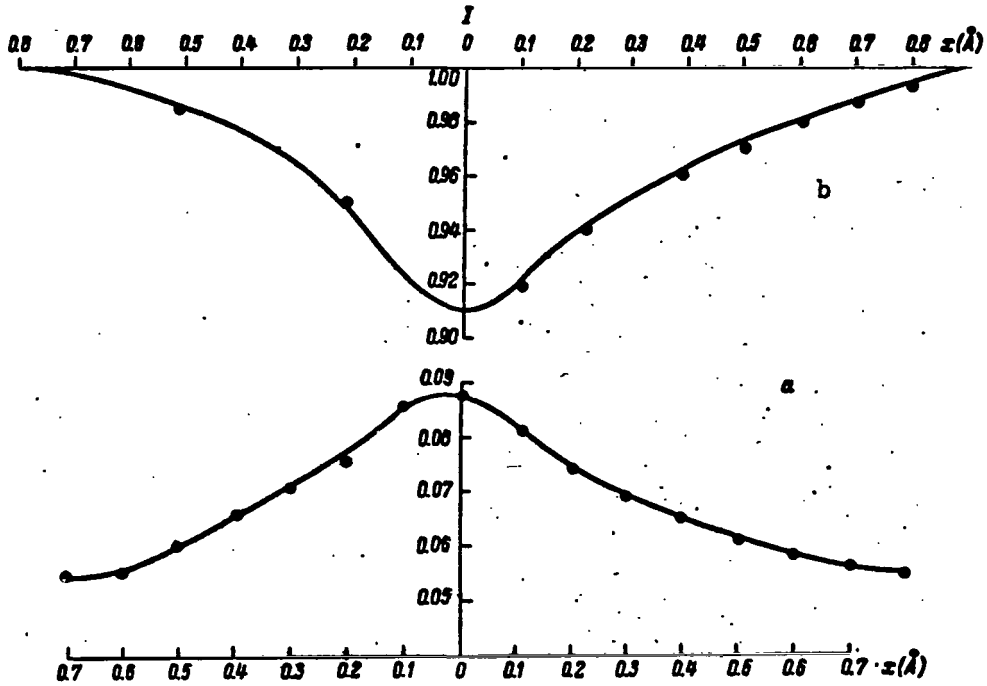

Figure 1. Line contours for D_3 line of solar flare of 3 September 1962. a - absorption; b - emission.

We attempted to determine the values of n_e and T_e by employing the method given in Ref. 3. We shall consider that the number of free electrons in helium streamers is equal to the total number of hydrogen atoms in the flare, i.e., $n_e = n_H$. Since the overall concentration of helium atoms (n_{He}) is one-fourth the concentration of hydrogen atoms (n_H), we obtain an equation for determining n_e of the form

$$4n_{^1He}\left(1 + \frac{n^+_{He}}{n_{^1He}}\right) = n_e . \qquad (3)$$

Here $n_{^1He}$ is the concentration of neutral helium atoms.

If we are given the values of n_e and T_e, we can again determine n_e by making use of the same tables and the observed values of n_{3D} and n_{2P}. Thus, we approach a pair of values for n_e and T_e, containing n_e, coinciding with that obtained from equation (3).

These values were found to be

$$n_e = 5 \cdot 10^{10} \text{ and } T_e = 2 \cdot 10^4.$$

Assuming that the optical thickness is small and the line is free of self-absorption, we can determine $\Delta\lambda_D$ from the total half-width of the lines ($\Delta\lambda$):

$$\Delta\lambda_D = \Delta\lambda/1.665. \qquad \text{/48}$$

In both cases, $\Delta\lambda_D = 0.36$ Å.

Making use of the obtained values of $\Delta\lambda_D$ and T_e, we computed the turbulent velocity (ξ_t) by the formula:

$$\left(\frac{\Delta\lambda_D}{\lambda} \cdot C\right)^2 = \frac{2RT_{min}}{M} + \xi_t^2,$$

where R is the gas constant, and M is the molecular weight. From this, $\xi_t = 16$ km/sec. This value for the turbulent velocity is similar to the values obtained for the chromosphere.

2. Contours of the H_α Line

Interpretation of the H_α contours is more complicated as the contours are of an irregular nature (Figure 2), and the wings of the lines have an excess of brightness as compared with the center. This is particularly pronounced in the contour associated with the formation on the disk.

We attempted to explain the observed form of the H_α absorption contour and to find its physical parameters.

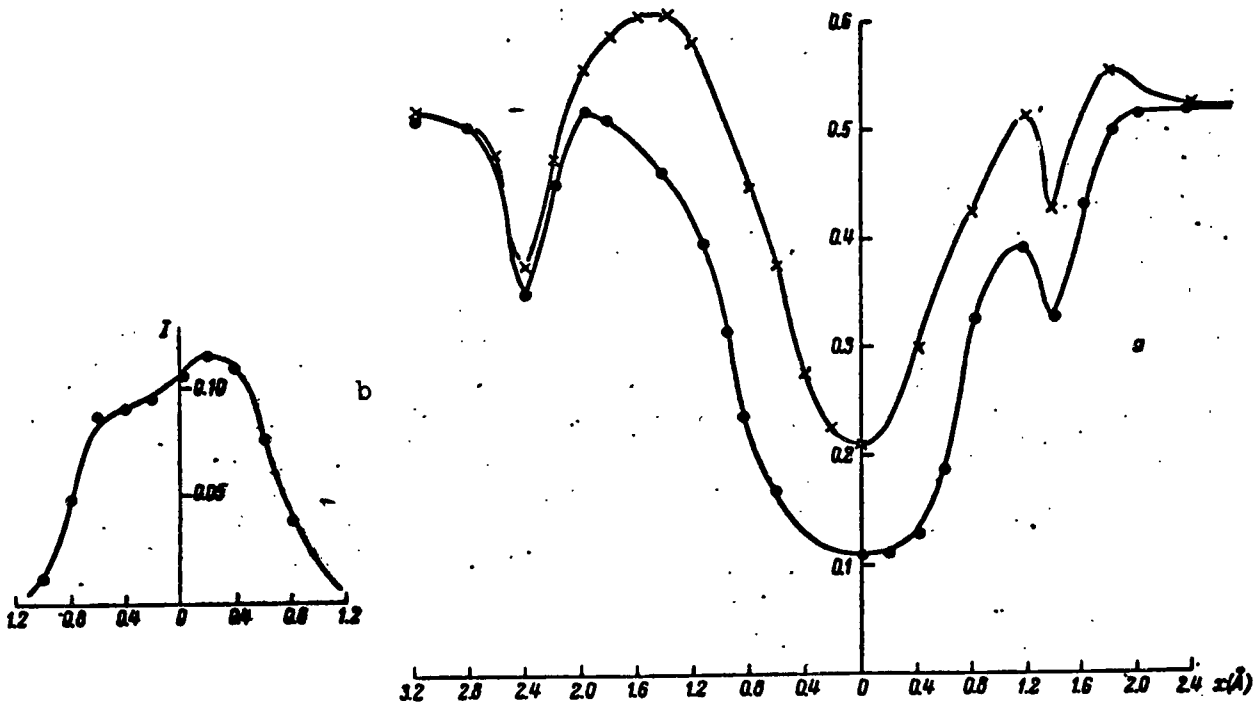

Figure 2. Line contours for H_α line of solar flare.

a - emission; b - absorption.

Since the observed flare was projected on the sun's disk, we should take account of the effect of the contour of the H_α Fraunhofer line, (the "base layer"), when considering the disturbed contour. /49

The contour of the absorption line of the area of the photosphere closest to the flare was chosen as the "base layer"; this contour did not show any deformations under the influence of the radiation field of the flare, since the contours of the "base layer" obtained for areas very close to the flare coincide with the contours for more distant areas.

The equation /50

$$i_\lambda = I_\lambda e^{-\tau} + P_\lambda (1 - e^{-\tau}) \qquad (4)$$

describes the contour of the flare with the effect of the "base layer" taken into account. Here, I_λ is the intensity of the Fraunhofer line, and P_λ is the function of the source in the flare.

In considering the contour, we immediately rejected the idea that we might have here superposition of two individual streamers with different radial velocities, since no noticeable radial velocity was observed in the contour of the D_3 line that was received at the same time, and the contour was symmetric.

The magnitude of the function of the source P_λ can be found theoretically, since it is expressed by the formula

$$P_\lambda = \frac{n_3}{n_2} \frac{A_{mn} h \nu_{nm}}{4\pi \sqrt{\pi} \Delta\lambda_D K_0} , \qquad (5)$$

where

$$K_0 = \frac{\sqrt{\pi} e^2 f_n \lambda^2}{mc^2 \Delta\lambda_D} ,$$

and is a function of only the ratio of populations on the levels (n_3/n_2). The value of n_3/n_2 was taken from tables included in an article by V. M. Sobolev (Ref. 4). This ratio has very slight dependency on T_e, and the concentration of atoms in the ground state (n_1), when $T_e \leqq 11,500^o$.

The temperature of the Lyman radiation T_2 was taken to be equal to T_e, i.e., the L_α radiation field was considered to be stationary.

The value of P_λ for $T_e = T_2 \leqq 12,000$ computed from equation (5) was found to be $1.30 \cdot 10^{13}$ CGS, while the value of the intensity of the continuous spectrum at the given wavelength was $3 \cdot 10^{14}$ CGS. Thus, the value of P was found to be equal to approximately 0.04 of the intensity of the continuous spectrum of the center of the sun's disk. This value of P was obtained with the condition, as shown in Ref. 4, that the population of the third level is created by photospheric radiation.

When a line is excited by scattering of photospheric radiation, the contour of the "base layer" should influence the magnitude of P_λ. More radiation passes through the wings of the contour than in the center; therefore, the value of P_λ should be greater in the wings than in the center.

Let us assume that P_λ is variable along the contour. Then $P_{wing} > P_{contour}$.

Equation (4) for the wing of a line, where the optical thickness τ decreases rapidly and we practically have the case of a thin layer, is written in the form

$$i_{wi} = I_{wi}(1 - \tau) + P_{wi}\tau,$$

since

$$\tau_{wi} \ll 1.$$

Otherwise /51

$$i_{wi} - I_{wi} = (P_{wi} - I_{wi})\ \tau_{wi},$$

where I_{wi}, P_{wi} and τ_{wi} are the respective values of I_λ, P_λ and τ_λ in the wings of the contour.

Making use of the data of the excited contour and the contour of the "base line", we obtain a value for P_λ in the wings of the contour:

$$P_{wi} = \frac{0.15}{\tau_{wi}} + 0.45 \gg 0.45$$

The intensity of the continuous spectrum at the given place on the disk for our contour is 0.52 of the intensity of the continuous spectrum in the center of the disk. This means that P_{wi} exceeds the value of the intensity of the continuous spectrum in the center of the disk.

This evaluation of P_λ in the central parts of the contour (P_{center}) was obtained with two assumptions: a) an optically thin layer ($\tau \ll 1$), and b) an optically dense layer ($\tau \gg 1$).

In the first case, P_{cen} was evaluated in a similar manner, but with different values of intensities

$$P_{cen} = \frac{0.10}{\tau_{cen}} + 0.11 \gg 0.11$$

In the case of an optically dense layer, equation (4) for the center of the line takes the form

$$P_{cen} = i_{cen} = 0.21$$

Consequently, depending on τ, we obtain the limits of change in P in the center of the line

$$0.11 \ll P_{cen} \ll 0.21.$$

Thus, no matter what the assumptions in regard to the optical thickness may be, we obtain P_λ for the flare, which is considerably larger along the entire contour than that for P_λ obtained by the tabular populations and corresponding to the case of photospheric scattering. Consequently, the observed radiation is not caused by scattering, and in that case the assumption of changes in P_λ along the contour is eliminated as the radiation itself does not depend on the radiation flux.

In order to explain the form of the contour as the result of the luminescence of a homogeneous layer, with the assumption that P is a constant over the entire contour, we examined two cases of different optical thicknesses of our formation.

With an optically thin layer, from equation (4) we obtain the distribution of $P\tau$ (by direct subtraction of the contour of the "base layer" from the excited contour) that maintains the form of the excited contour, which contradicts the assumption of a small value of τ, since in that case the value of $P\tau$ would be maximum in the center of the contour.

This means that the assumption of radiation from the thin layer itself is not justified.

Let us consider the case of a thick optical layer. /52

From equation (4) we obtain for the center of the line

$$i_0 = P . \qquad (6)$$

We shall rewrite equation (4) in the form

$$i_\lambda - P = (I_\lambda - P) e^{-\tau}$$

or, taking (6) into consideration, we obtain

$$i_\lambda - i_0 = (I_\lambda - i_0) e^{-\tau_\lambda} \qquad (7)$$

Since it is always true that $e^{-\tau_\lambda} > 0$, then both differences in equation (7) should always be of the same sign, and since $I_\lambda < i_0$ in the central parts of the line, then it should also be true that $i_\lambda < i_0$.

In the wing of the line, where $\tau \ll 1$, we obtain from (7):

$$i_\lambda - I_\lambda = (i_0 - I_\lambda)\, \tau_{wi};$$

since

$$\tau_{wi} = \frac{i_\lambda - I_\lambda}{i_0 - I_\lambda} \ll 1,$$

then

$$i_\lambda - I_\lambda \ll i_0 - I_\lambda .$$

Consequently, $i_{wi} \ll i_0$.

Thus, the radiation from an optically dense layer also yields an emission contour with the maximum value of the intensity in its center.

This means that the case of large τ values does not explain the form of the contour.

Consequently, regarding a flare as a homogeneous streamer cannot explain the form of the H_α contour for any values of the optical thickness and any assumptions concerning the conditions of excitation.

Thus, it is essential to present for consideration a two-layer model of a flare as a bright and hot emission streamer characterized by the quantities (P_1, τ_1) which are surrounded by a colder absorbing layer with the parameters (P_2, τ_2).

Analogous models for stronger formations have been examined by other authors (Ref. 5).

The external layer of gas will attenuate the radiation from the interior layers as $e^{-\tau_2}$. The attenuation of the "base layer" will be characterized by the quantity $e^{-(\tau_1+\tau_2)}$.

Thus, the observed intensity will be expressed by the equation

$$i_\lambda = I_\lambda e^{-(\tau_1 + \tau_2)} + P_2 (1 - e^{-\tau_2}) + P_1 e^{-\tau_2}(1-e^{-\tau_1}). \qquad (8)$$

We shall consider that $P_2 \ll P_1$, for otherwise the radiation from the central streamer would not reach us. Thus, $\tau_1 + \tau_2 \gg 1$ in the center of the line. Then we shall have in the center of the line

$$i_0 = P_1 e^{-\tau_2} + P_2 (1 - e^{-\tau_2});$$

and since /53

$$P_2 e^{-\tau_2} \ll P_1 e^{-\tau_2},$$

we obtain the equation

$$i_0 = P_1 e^{-\tau_2} + P_2 .$$

In a like manner, we obtain for the wing of the line, where $\tau \ll i$,

$$i_\lambda = I_\lambda (1 - \tau_1 - \tau_2) + P_2 \tau_2 + P_1 \tau_1 (1 - \tau_2) . \qquad (9)$$

Since more radiation passes through the wings of the observed contour than through the center, we shall consider the contour of the outer absorbing layer to be narrower. Then $\tau_2 \ll \tau_1$ in the wing of the line and equation (9) is reduced to the form

$$i_{wi} - I_{wi} = (P_1 - I_{wi}) \tau_1 .$$

Starting with the data of the contour, we obtain an estimate of P_1 from this

$$P_1 \gg 0.45 .$$

Having only the one H_α line, we cannot determine the exact values of P_1, P_2, τ_1 and τ_2.

However, even in this case it can be concluded that the value of the function of the source in the interior layers of the flare (P_1) exceeds the value we obtained theoretically.

The same result is also obtained from the H_α emission contour, where the effect of the "base layer" can be neglected (Figure 2b).

The intensity of the contour will then be determined by the formula

$$i = P(1 - e^{-\tau}) .$$

It can be seen from this that $P \geqslant i$ for any τ, but since the central intensity of the emission contour is 0.11 of the intensity of the continuous spectrum, P should again considerably exceed the theoretical value of P.

We did not apply the two-component model to this contour, but the increased value of the function of the source, which is also obtainable for the emission contour, is again a possible confirmation of the generality of the physical conditions in both formations.

Thus, we have concluded that the hydrogen luminescence cannot be explained by scattering by photospheric radiation, and is caused by the increased population of the third level (since P is a function of n_3/n_2).

When $T_e = T_2 \geq 1.5 \cdot 10^4$, as is shown in the tables of Ref. 4, the population of the third level should be increased noticeably, and this increase is quite sufficient to explain the value of P obtained from observations when $1.5 \cdot 10^4 \leqq T \leqq 2 \cdot 10^4$. With this high temperature, excessive population of the third level will create electron shock. This high temperature value is possible for hydrogen as its ionization increases comparatively slowly with temperature; and, moreover, the population of the higher levels increases with increased T_e. Apparently, in this case hydrogen and helium can radiate light in the same part of a flare. We did not suceed in obtaining exact values /54 for $T_e = T_2$, since the tables did not contain figures for such large T_2 and we obtained the limits of the value of T_e by extrapolating from the tables to get larger values of T_2.

In conclusion, we wish to express our sincere thanks to V. A. Krat for his guidance and advice in carrying out this work.

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